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28JUL99 E465199-1 D02917
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The Patent Office
27 JUL 1999
THE PATENT OFFICE
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Request for grant of a patent

The Patent Office
Cardiff Road
Newport
Gwent NP9 1RH

1. Your reference
5314301/IM

2. Patent Application Number **9917610.9**

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

27 JUL 1999

Cambridge Consultants Limited
Science Park
Milton Road
Cambridge CB4 4DW

Patents ADP number *(if known)* 361618001

If the applicant is a corporate body, give the country/state of its incorporation
Country: UNITED KINGDOM
State: UNITED KINGDOM

4. Title of the invention
IMPROVEMENTS IN OR RELATING TO SPECTROMETERS

5. Name of agent **Beresford & Co**

"Address for Service" in the United Kingdom to which all correspondence should be sent
2/5 Warwick Court
High Holborn
London WC1R 5DJ

Patents ADP number 1826001

6. Priority details

Country	Priority application number	Date of filing

*****please enter priority details******

Patents Form 1/77

7. If this application is divided or otherwise derived from an earlier UK application give details

Number of earlier of application | Date of filing

insert filing date

8. Is a statement of inventorship and or right to grant of a patent required in support of this request?

YES

9. Enter the number of sheets for any of the following items you are filing with this form.

Continuation sheets of this form

Description 15

Claim(s) 6

Abstract 1

Drawing(s) 15

10. If you are also filing any of the following, state how many against each item.

Priority documents

Translations of priority documents

Statement of inventorship and right to grant of a patent *(Patents form 7/77)* 1

Request for preliminary examination and search *(Patents Form 9/77)* 1

Request for Substantive Examination *(Patents Form 10/77)*

Any other documents *(please specify)*

11. I/We request the grant of a patent on the basis of this application

Signature ______________________ Date 27 July 1999

BERESFORD & Co

12. Name and daytime telephone number of person to contact in the United Kingdom

IAN MACKENZIE

Tel:0171-831-2290

IMPROVEMENTS IN OR RELATING TO SPECTROMETERS

The present invention concerns interferometers and is particularly concerned with Fourier transform spectrometers. Fourier transform spectroscopy is a well known technique for obtaining the spectra of weak extended sources. It offers throughput and multiplex advantages which can give rise to superior signal-to-noise performance when compared to other methods.

As a result there has been an increasing demand for Fourier transform spectrometers over a wide range of applications including industrial, medical, environmental and consumer applications.

Accordingly there has been a trend of simplifying and ruggidising spectrometer instrumentation to enable it to be used in an extended range of applications. There is however a trade-off between performance and cost associated which tends to limit the range of applications of emerging products.

The present invention is particularly concerned with

providing an extremely simple and robust component for a spectrometer.

In one aspect the invention provides a two component optical block in which light to be analysed is internally reflected and combined to produce an interference fringe pattern which can be measured to provide a spectral analysis of the light.

In order that the invention may be more readily understood embodiments thereof, and of the prior art, will now be described by way of example and with reference to the accompanying drawings in which:

Figure 1 is a schematic view of a known Michelson interferometer;

Figures 2A and 2B show respectively a fringe function and a spectrum;

Figure 3 is a schematic diagram of another known

form of interferometer;

Figure 4 shows the basic component of an optical block in accordance with a first embodiment of the present invention;

Figure 5 is similar to Figure 4;

Figure 6A and 6B shows steps in the manufacture of the optical block of Figure 5;

Figure 7 is an illustration of a second embodiment of an optical block in accordance with the present invention;

Figure 8 is similar to Figure 7;

Figure 9 is similar to Figure 8 but has certain dimensions exaggerated in the interest of clarity;

Figure 10 is a diagram showing another embodiment of

an optical block;

Figure 11 is a diagram illustrating a particular practical realisation of an embodiment of an optical block in accordance with the present invention;

Figure 12 is a diagram showing another practical implementation of an optical block in accordance with the present invention;

Figure 13 is a diagram illustrating a third practical implementation of an optical block in accordance with the present invention;

Figure 14 is a diagram of spectrometer according to the present invention; and

Figure 15 shows two spectral waveforms.

Referring now to Figure 1 this shows the conventional form of an instrument based on a Michelson

interferometer. In this arrangement the interference fringe field formed due to the superposition of the light field U_1 and U_2 reflected respectively from the mirrors M_1 and M_2 via the beam splitter B is incident on a light sensitive detector P. The aperture of this detector is made considerably smaller than the fringe spacing in the plane of detection. The output of this detector thereby defines the interference fringe intensity distribution generated as the mirror M_2 is translated. In Fourier transform spectroscopy this translation is arranged to occur over a distance $\pm$ D about the point where the path length in the translated arm of the interferometer l_2, matches that of the other arm, l_1. Figure 2 shows the form of the fringe envelope observed under these conditions where i (τ) is photo current of the detector P as a function of the mirror displacement $\pm$ D. Note that i (τ) is proportional to the interference fringe pattern

$$I_{12} = I_1 + I_2 \times 2\sqrt{I_1 I_2}\gamma(\tau)\frac{4\Pi D}{\lambda} \qquad (1)$$

where

I_1	=	intensity of interfering beam U_1
I_2	=	intensity of interfering beam U_2
$\gamma(\tau)$	=	coherence function of source
τ	=	D/C
λ	=	wavelength at light
c	=	speed of light

$\gamma(\tau)$ is equal to the correlation of the two beams of light with a relative delay time $\tau = D/c$ i.e.

$$\gamma(\tau) = f(t)f^*(t+\tau) / \overline{|f(t)|^2} \qquad (2)$$

Where

f(t) = defines interfering waveform as function of time, t.

By the Wiener-Khinchin theory, the Fourier transform of $\gamma(\tau)$ is equivalent to the spectral intensity $I(\omega)$. Hence the Fourier transform of the fringe function generated in the specific way described provides a measure of the spectral distribution of the input light field as is shown schematically in Figure 2. It may be shown that the resolution of this type of spectrometer is

given by

$$\left(\frac{\delta\lambda}{\lambda}\right)_{min} = \frac{\lambda}{2D_{max}} \qquad (3)$$

where D_{max} = maximum amplitude of mirror displacement

Hence a value of D = 100μm will generate a wavelength resolution of under 1nm for λ = 500nm.

In practice the translation mechanism has to be extremely precise in order to minimise variations in the fringe spacing and vibration across the detector since such variations also cause a modulation of the fringe envelope and introduce errors in the resultant spectrum. This problem is usually minimized by the use of corner cube reflectors but nonetheless these are expensive the instrument still requires a precision positional encoder to define the transform time scale (D/c).

Moving parts can be eliminated by using the arrangement shown in Figure 3 in which the mirror M_2 is rotated by an angle ε about an axis co-incident with the zero-order fringe. A distributed fringe field is then observed which is imaged in the plane of a pixellated detector array DA by the lens L. The fringe field

envelope is then defined by the spatially scanned output of the detector array and is equivalent of that shown in Figure 2 but does not require the translation of a mirror.

Various configurations of interferometer are described in the prior art which are aimed at simplifying and ruggedising the extended fringe field interferometer described above. These include the use of a polarising/birefringent elements to reduce the system to a common path interferometer and a common path, contra propagating three element Sagnac configuration.

Referring now to Figure 4 of the drawings this shows an optical block which comprises two optical elements 1 and 2 which may be fabricated from conventional good quality optical materials such as BK7 glass. The term optical block is used to define the optical components in which the interference fringe field is actually generated.

The optical block shown in Figure 4 has a common central element BS/C which acts as a beam splitter and combiner and is placed between reflectors R_1 and R_2. The

planes of R_2, BS/C and R_1 are nominally parallel and R_1 and R_2 separated by a distance of respectively S_1 and S_2 from BS/C. An input beam U_1 of diameter a_i is incident at angle θ to the surface normal of BS/C such that adjacent beams incident on R_1 and R_2 do not overlap. This requires that $\theta > \sin^{-1}2S_{1,2}/a_i$. Under these conditions it can be seen that two beam interference will occur between various combinations of beam propagating through and exiting from the R_1, $R_{2.}$ BS/C structure (e.g. at d and f).

In the embodiment shown in Figure 4 the interfering beams are reflected once from the outer reflectors. The input beam is split at BS/C into the reflected and transmitted components U_r, U_t respectively. These are in turn reflected from R_1 and R_2 and recombine at B/SC. The interferogram described by equation 1 is generated by arranging for the faces R_1 and R_2 to be inclined at a total angle ε with respect to one another. This is more clearly shown in Figure 5 whilst ensuring that the zero order fringe for which S_1=S_2 is nominally at the centre of the fringe field. The fringes will localise i.e. have maximum contrast in the plane which the interfering beams

intersect as shown in Figure 5. In practice a lens is used to form an image of the localised fringe field in the plane of the detector array.

A preferred embodiment of this interferometer may be fabricated from a single wedge cut into two wedges along the wedge section as shown in Figure 6. One wedge is then rotated in its plane by 180°C about the cut orientation and its lower face cemented to that of the other prism to form the monolithic element or optical block shown. An input beam 3, output lens 4 and sensor array 5 are also shown. In order to maximise the optical throughput the reflection coefficients of R_1 and R_2 should be as near 1.0 as possible and transmission (t) of reflection (r) coefficients of BS/C should both be equal to 0.5. The sensor array may be any suitable pixellated semiconductor array such as a CCD array.

A key objective in fabrication is to maintain repeatability of fringe geometry. In the above configuration this will depend upon the extent to which the wedge alignment and attachment process causes variations of the orientation of R_1 and R_2 relative to

the reference wedge angle $\varepsilon/2$. Sensitivity to alignment tolerance is relaxed relative to for interferometric precision required in the latter case when the number of reflections at R_1 and R_2 is extended from 1 to 2 as shown in Figure 7. Under these conditions the interfering beams are common to R_1 and R_2 and relative misorientation of the latter do not therefore effect the fringe spacing.

An angular separation between the interfering beams in this dual reflection geometry is formed either by tilting one or a combination of the section of each reflector upon which an individual beam is incident. If the sections A,B,C,D of the reflectors shown in Figure 8 delineate the regions over which there is no overlap of the incident beams they therefore define the sections that may be tilted relative to one another.

Figures 9 and 10 show respectively the arrangement in which section A and sections A&B are tilted. Here it will be noted that the only requirement when two sections are tilted is that the tilts be in an opposite sense so that the angular displacement created by the first is not compensated by the second. The position of the zero

order fringe will also be a function of the relative tilt of the two reflectors since this will define the point for which the path lengths of the two interfering beams are equal. In the case of Figure 9 (A tilted only) the zero fringe will occur at the extreme edge of the interference field. This position will shift towards the centre as B is tilted in the opposite sense (Figure 10) and will be at the centre of the fringe field when the tilts of the two mirrors are equal. Note that a lateral shift of the dual angle reflector relative to the flat provides a means of fine tuning the position of the zero order fringe.

For one class of preferred configuration the tilts are confined to the R_1 element so that the BS/C and R_2 functions may be combined on a single optical flat with parallel faces. Figure 11 illustrates how the optical block is formed by such an optical flat located on an element M which incorporate the symmetrically tilted reflector R_1. In practice M could be a precision moulded component and the optical block assembled by inserting the flat F in the pre-moulded location. This procedure

is compatible with low cost components and manufacture since as has been noted above, this configuration of the optical block is not dependent on the precision location of R_1 with respect to R_2.

Figure 11 also shows the additional components the system consisting of an extended source S (which may in practice consist at a large core optical fibre), collimating/focussing input lens L_1, output fringe and field imaging element L_o and detector array A. These elements will, in general, be required for all geometrics at the interferometer.

Figure 12 shows an alternative way of manufacturing the optical block in which the optical flat G is attached directly to the dual angle prism H. This arrangement is particularly robust and could, for example, be manufactured from low expansion glass to enable operation at elevated temperatures. Figure 12 shows the same basic design in which all faces are mutually tilted. This configuration could be manufactured by slicing and rejoining a dual angle prism in accordance with the principle indicated in Figure 7 for a single angle (i.e.

wedge) prism.

In order to maximise the optical throughput the outer reflection R_1 and R_2 should have a coefficient of reflectivity as near to unity as possible and the reflection (r) and transmission coefficients r,t at BS/C should be respectively .33 and .66. These coefficients should apply over the spectral range of operation.

Figure 14 shows schematically a typical practical implementation of the optical blocks just described in an interferometer. Here light from a source S is coupled to a region of test T via a beam splitter B.

In this configuration T may be a sample for which it is required to measure the spectral reflectivity. Alternatively T may be a passive reflector and the spectral transmission of the medium between the light delivery element and T measured. In either case light is coupled into the interferometer I via the current lens L_i and imaged onto the detection array DA by the output lens L_o. In a preferred configuration all of the elements external to the interferometer may in practice be integrated with the structure at the optical block of the

interferometer by combining, for example, moulded light guides and lenses with the reflective elements. The output of the detection array can be Fourier transform analysed in a well known manner by a suitable processor PC for display or printing.

Figure 15 is an example of a preliminary experimental result which shows the spectrum of the same source measured using a calibrated spectrometer and that obtained using a laboratory version of the dual reflection spectrometer described above.

It will be appreciated that the optical blocks just described are compatible with robust monolithic fabrication of the two elements. With respect to the current state of the art it therefore reduces cost by eliminating the need for specialised components whilst simplifying manufacture by virtue of the reduction in component number.

CLAIMS:

1. An interferometric optical block having three planar nominally parallel surfaces with the two outer surfaces adapted to act as beam reflectors for internal light and the third surface in operation acting as a beam splitter and beam combiner, the optical block having an input portion by means of which an input beam of light to be analysed can be input so as partially to pass through said third surface to be internally reflected by one of said outer reflectors, and partially to be reflected by said third surface so as then to be internally reflected by the other of said outer reflectors whereby light internally reflected by said outer reflectors is combined at said third surface to produce an exit beam, and wherein said outer surfaces have an inclination with respect to one another so as to make a variation in path lengths in the light forming the exit beam so as to generate an interference fringe field.

2. An optical block in accordance with claim 1 in which the exit beam results from the interference of the beams

transmitted and reflected from the beam splitter/combiner that have in operation each undergone a single reflection at the outer reflectors.

3. An optical block in accordance with claims 1 or 2 which has been fabricated by cutting a single wedge element parallel to the wedge section to create two identical wedges and with one such wedge so cut rotated 180°, the lower face of said one wedge being secured to the other wedge to form a monolithic element, the adjacent faces of the wedges forming said third surface.

4. An optical block in accordance with claim 1 in which the exit beam in operation results from the interference of beams combined at the beam splitter/combiner which have undergone two reflections at the outer reflectors.

5. An optical block in accordance with any preceding claim in which the beam splitter/combiner and one reflector are formed by an optical flat with parallel faces and the other reflector is provided by a single

unit comprising the inclined mirror or mirrors and an integral location for the optical flat.

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6. An optical block in accordance with any one of claims 1 to 4 in which the beam splitter/combiner and one reflector are formed by an optical flat with parallel faces and the other reflector by a solid prism with one plane face and an inclined second face, the block having been assembled by attaching the plane fact of the solid prism to the plane beam splitter/combiner face of the optical flat.

7. An optical block in accordance with any one of claims 1 and 4 fabricated from two identical solid dual angle prisms where the plane faces are attached to form the beam splitter combiner and the outer identical and mutually inclined faces form the reflectors.

8. An optical block in accordance with claim 7 in which the prisms have been obtained by cutting in two a single dual angle prism in a plane parallel to the dual angle

section.

9. An optical block according to any one of the preceding claims wherein in order to maximise optical throughput over the spectral range of operation said beam splitter/combiner and reflector surfaces are coated with a coating such that the reflectivity coefficient of the reflectors is approximately 1.0 and the transmission coefficient and reflection coefficient being respectively 0.5 and 0.5 for the single reflection configuration and .66 and .33 for the dual reflection configuration.

10. An optical block in accordance with any preceding claim including a lightguide or optical fibre associated with said input portion.

11. An interferometer comprising an optical block as claimed in any one of the preceding claims, a light source for directing light to be interferometrically analysed to the input portion of said block so that the light beams incident on the reflectors and the beam

splitter/combiner do not overlap, and a light sensor array for detecting the pattern of the fringe field, the fringe field having a multiplicity of fringes about a zero order fringe so that a Fourier transform of said fringe pattern corresponds to the spectral distribution of the illumination source.

12. A spectrometer according to claim 11, comprising a lens system adapted to form an image of the optimum contrast fringe field as localised on a plane relative to the inteferometer onto said sensor array, and wherein said sensor array comprising is a pixellated semi-conductor array.

13. A spectrometer according to claim 12 and including electronic processor adapted to generate the Fourier transform of the electrical signal generated by said array so as to measure the spectral distribution of the input light.

14. A spectrometer according to any of claims 11 to 13

comprising means for coupling light to and from the measurement zone, imaging light into interferometer and imaging the fringe field light out of optical block onto the detector array form an integral element of the interferometer.

ABSTRACT

IMPROVEMENTS IN OR RELATING TO SPECTROMETERS

The present invention concerns spectrometers which utilise an interferometric optical block having three planar nominally parallel surfaces with the two outer surfaces adapted to act as beam reflectors for internal light and the third surface in operation acting as a beam splitter and beam combiner, the optical block having an input portion by means of which an input beam of light to be analysed can be input so as partially to pass through said third surface to be internally reflected by one of said outer reflectors, and partially to be reflected by said third surface so as then to be internally reflected by the other of said outer reflectors whereby light internally reflected by said outer reflectors is combined at said third surface to produce an exit beam, and wherein said outer surfaces have an inclination with respect to one another so as to make a variation in path lengths in the light forming the exit beam so as to generate an interference fringe field.

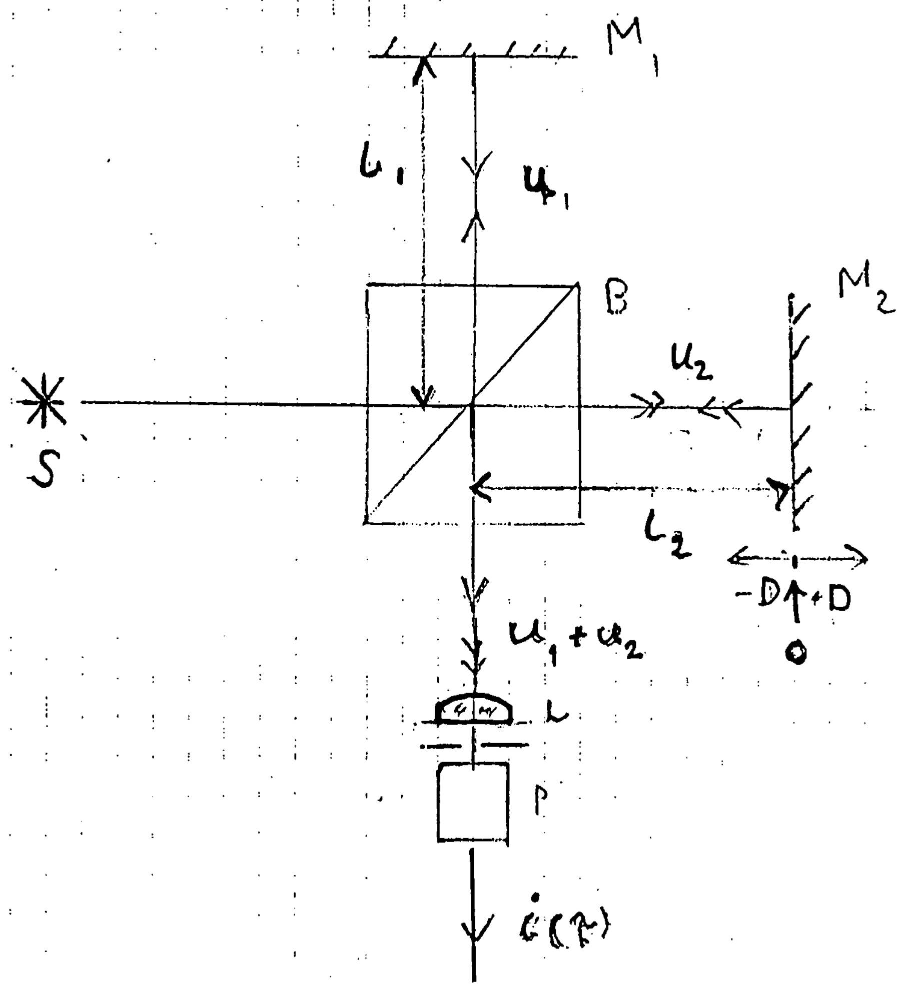
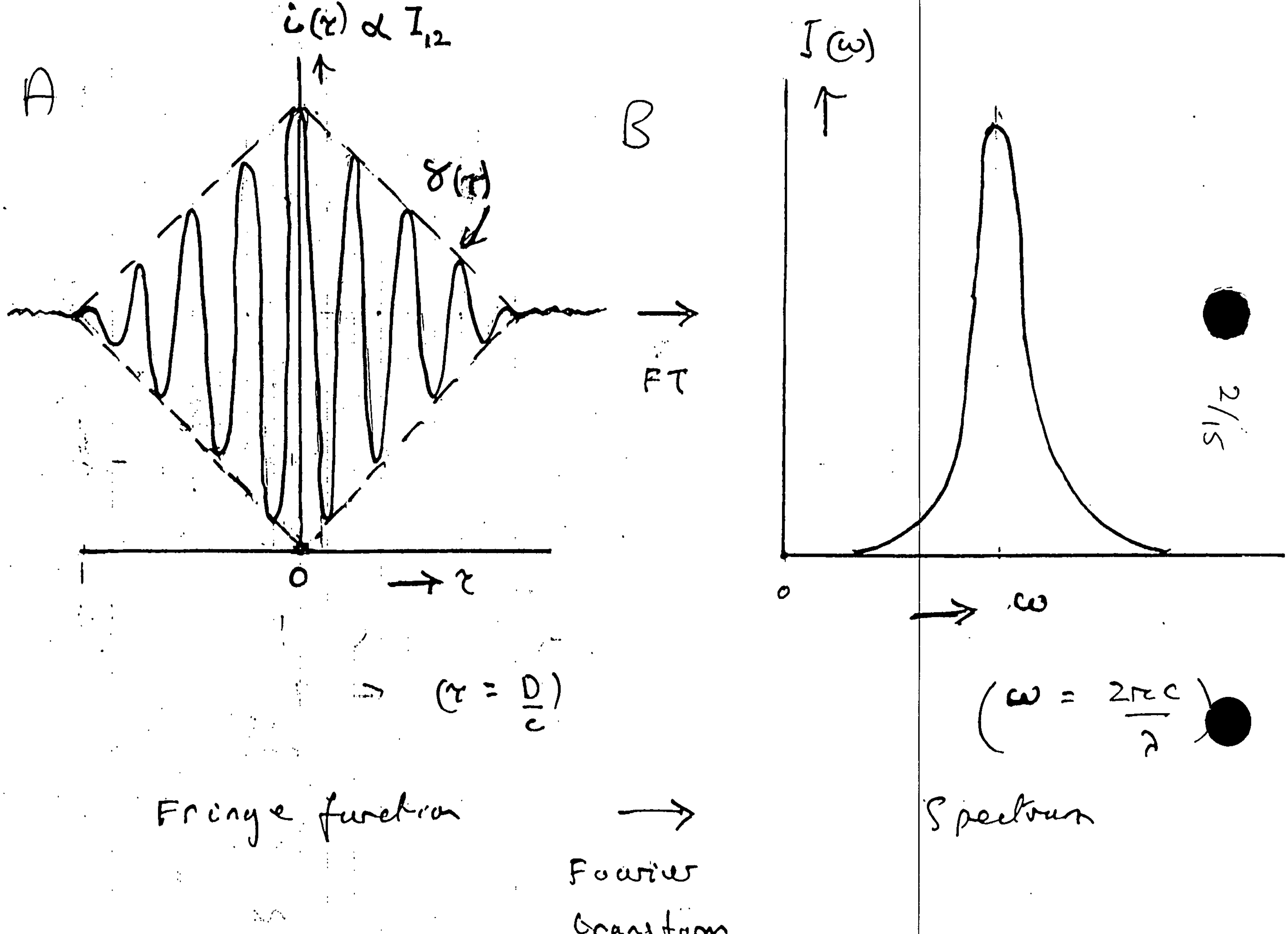


FIGURE 1



A
B
$i(\tau) \propto I_{12}$
$\gamma(\tau)$
0
$\rightarrow \tau$
FT
$I(\omega)$
0
$\rightarrow \omega$
$(\tau = \frac{D}{c})$
$(\omega = \frac{2\pi c}{\lambda})$
Fringe function
Fourier transform
Spectrum

FIGURE 2

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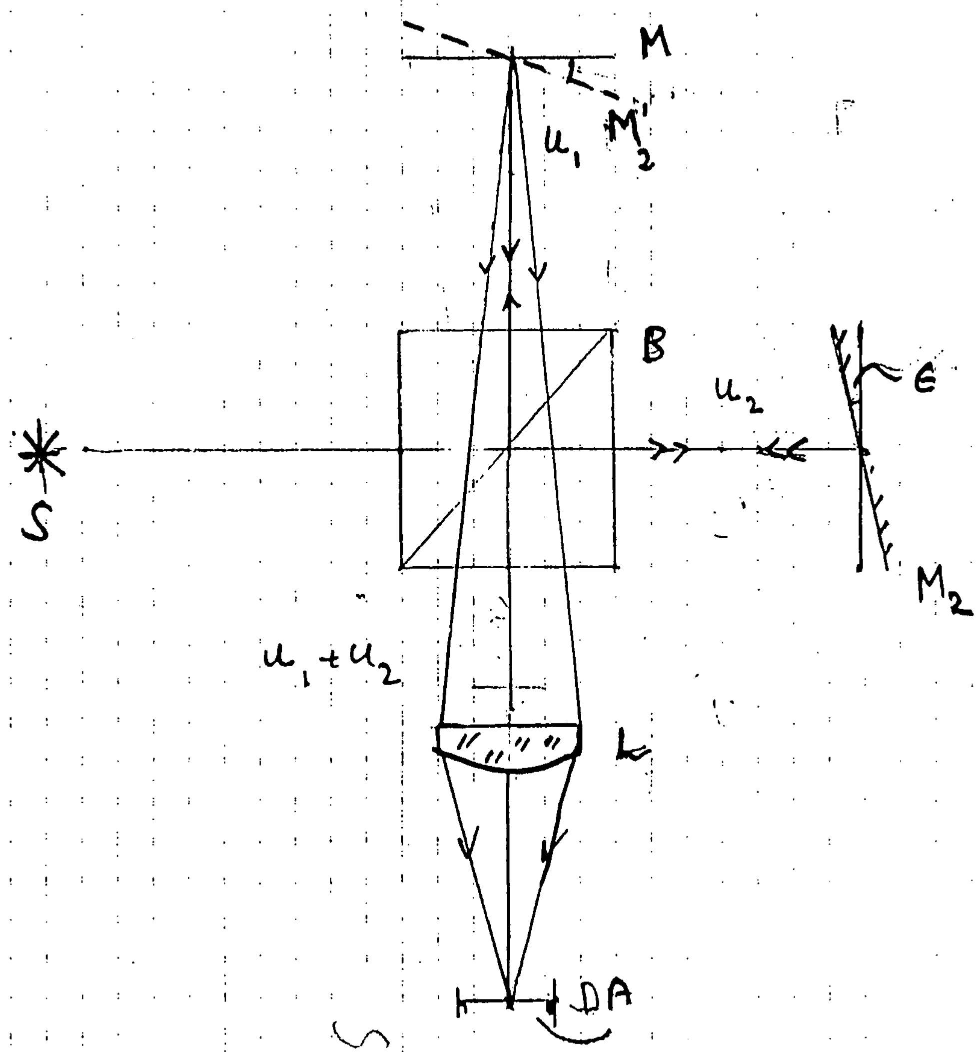

Spare

FIGURE 3

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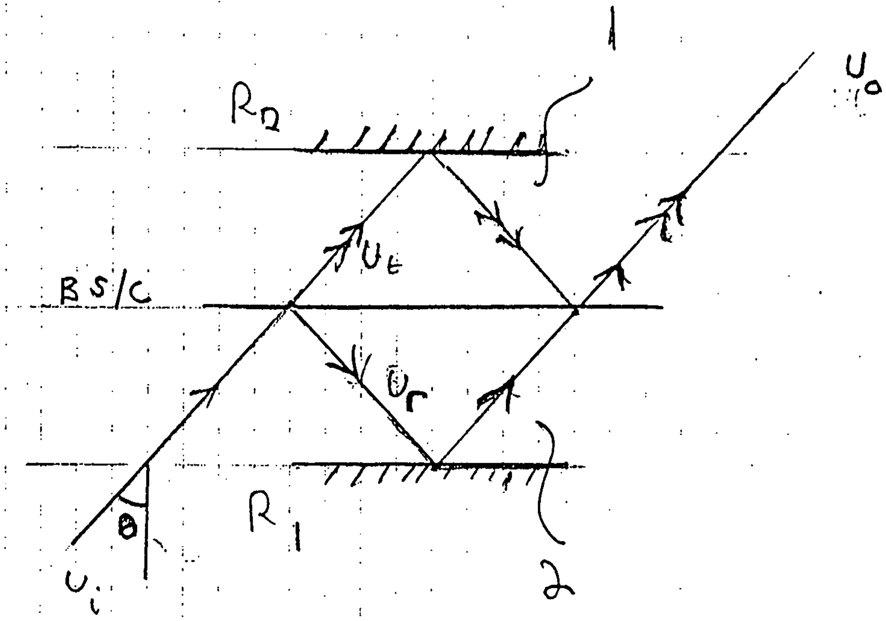

FIGURE 4

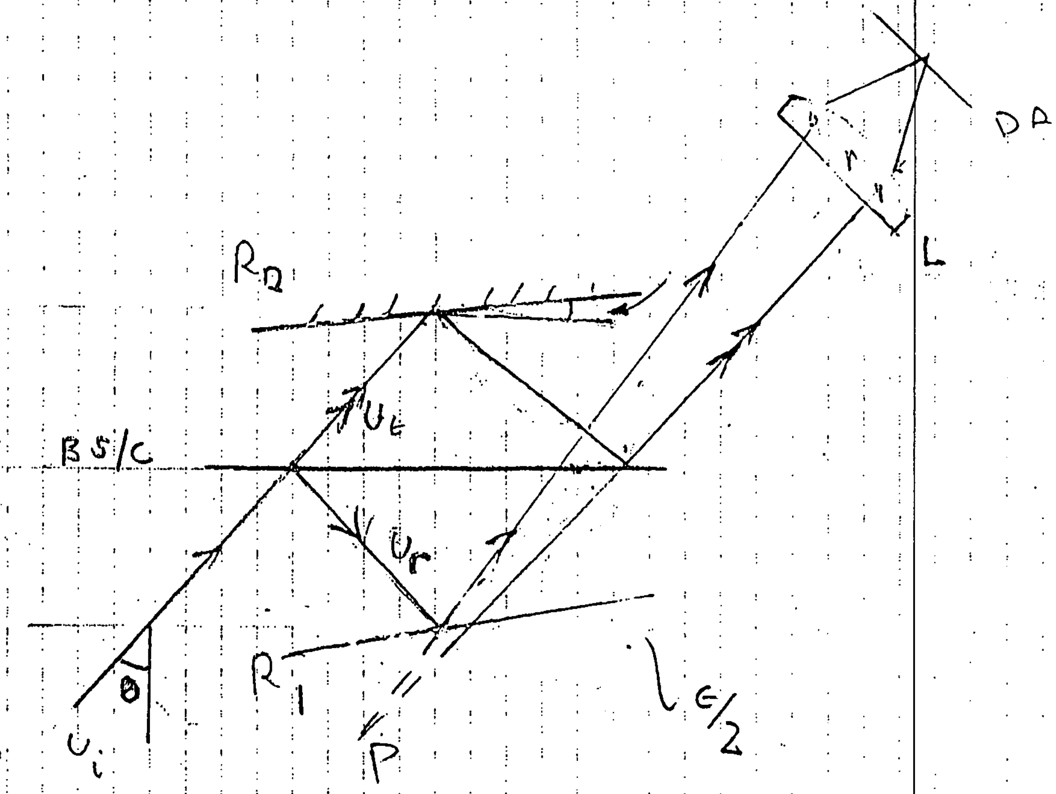

FIGURE 5

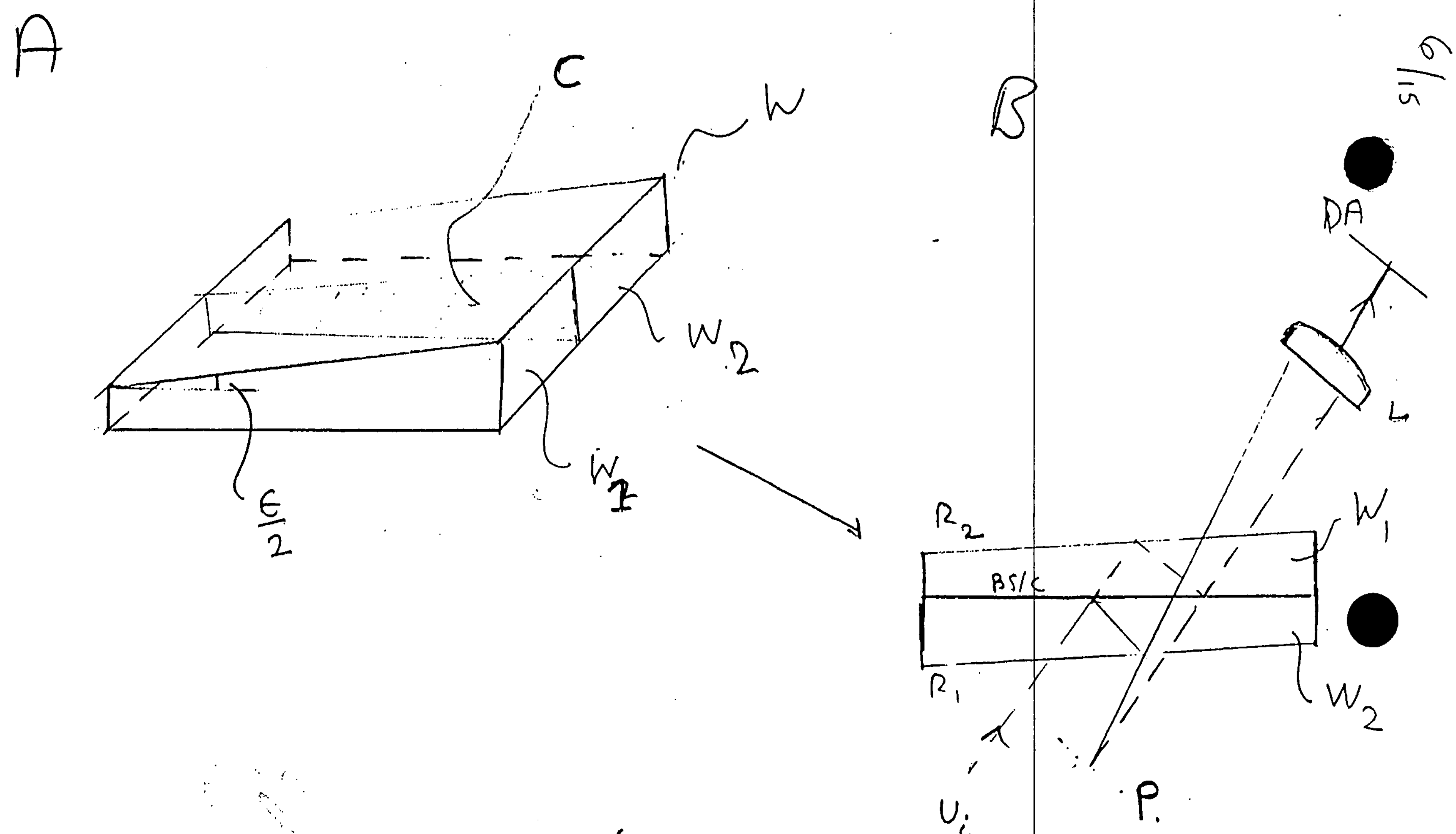

FIGURE 6

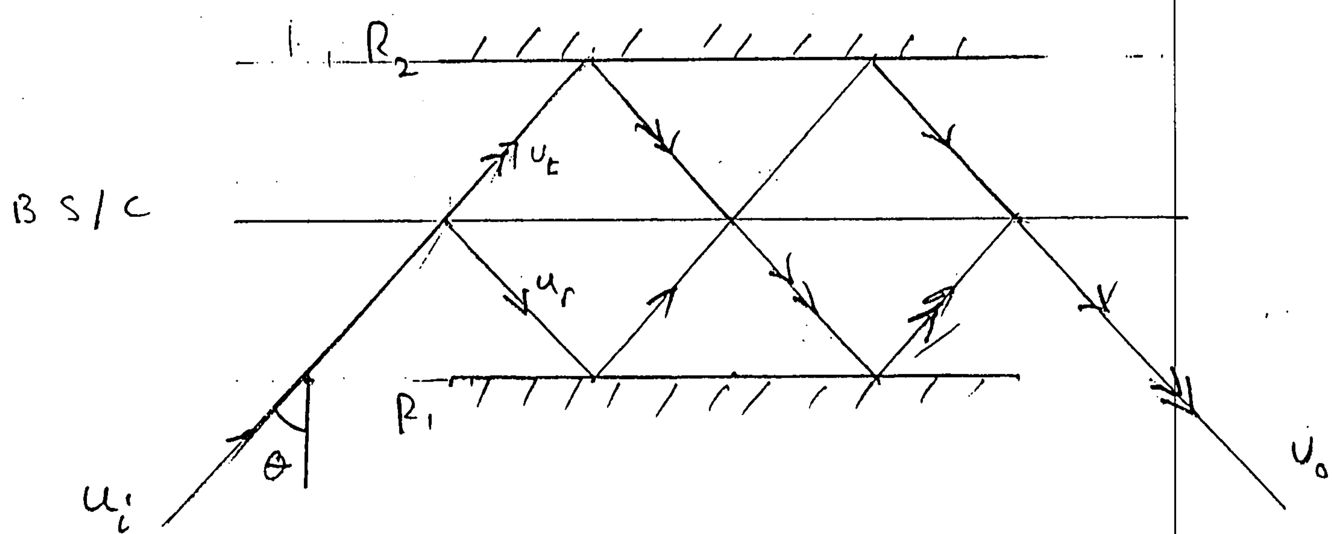

FIGURE 7

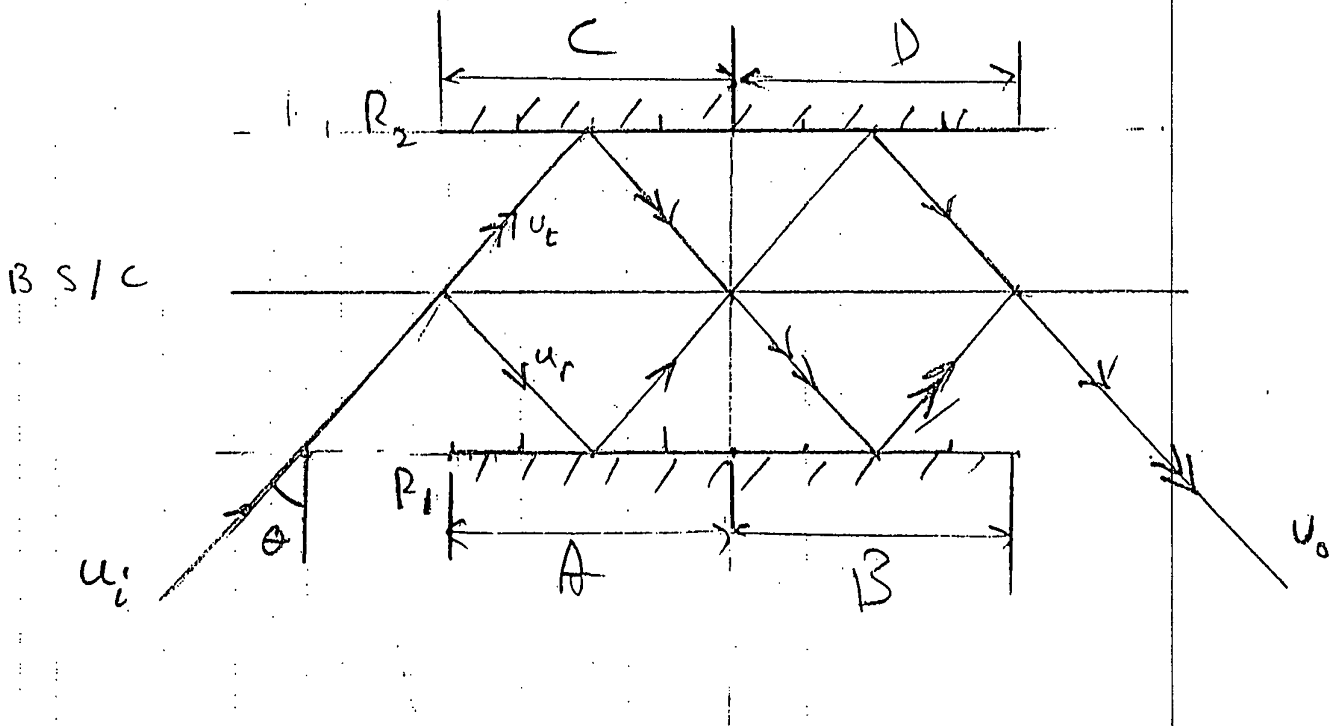

FIGURE 8

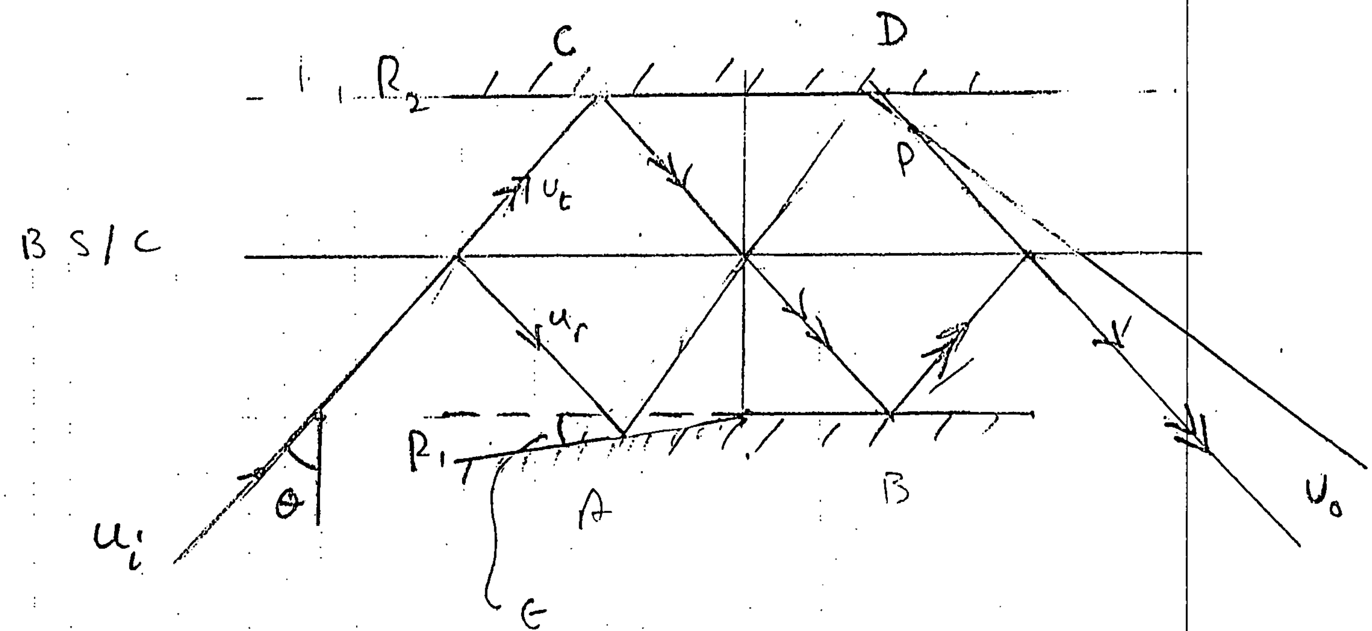

FIGURE 9

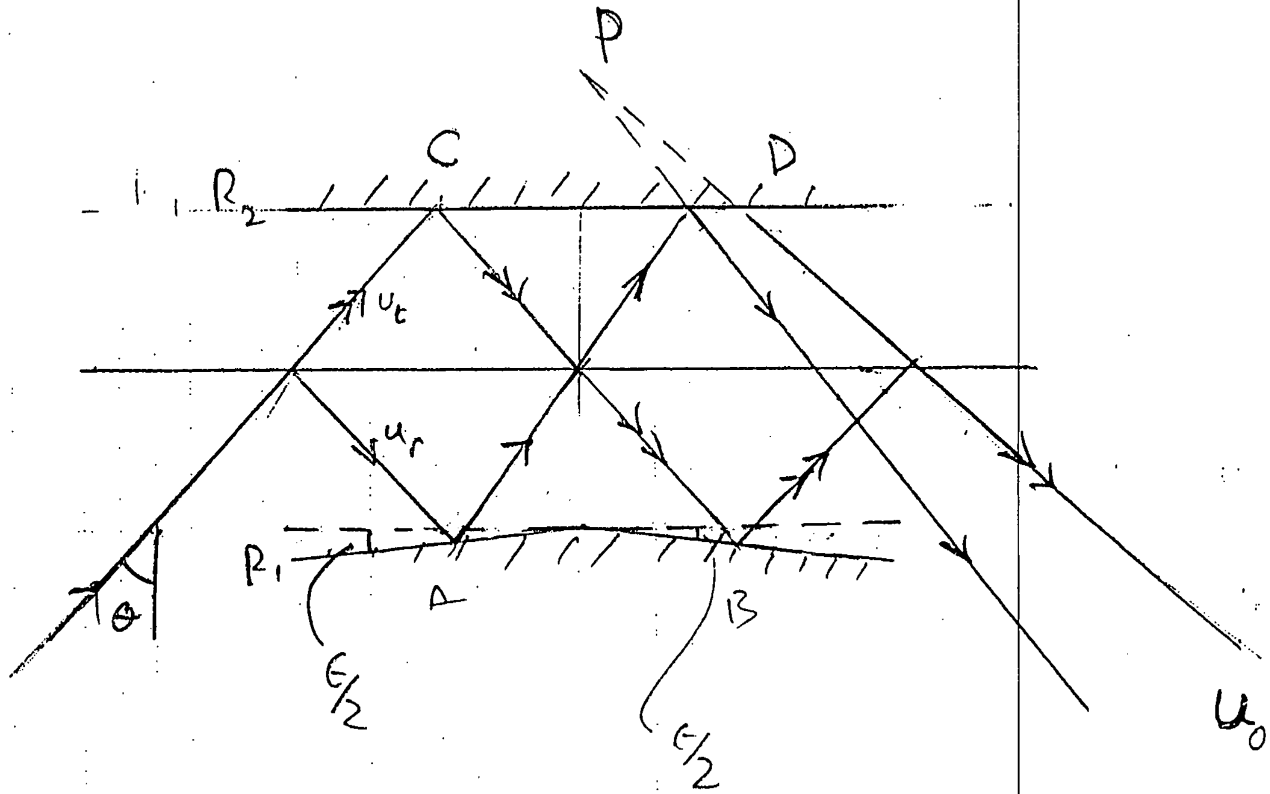

FIGURE 10

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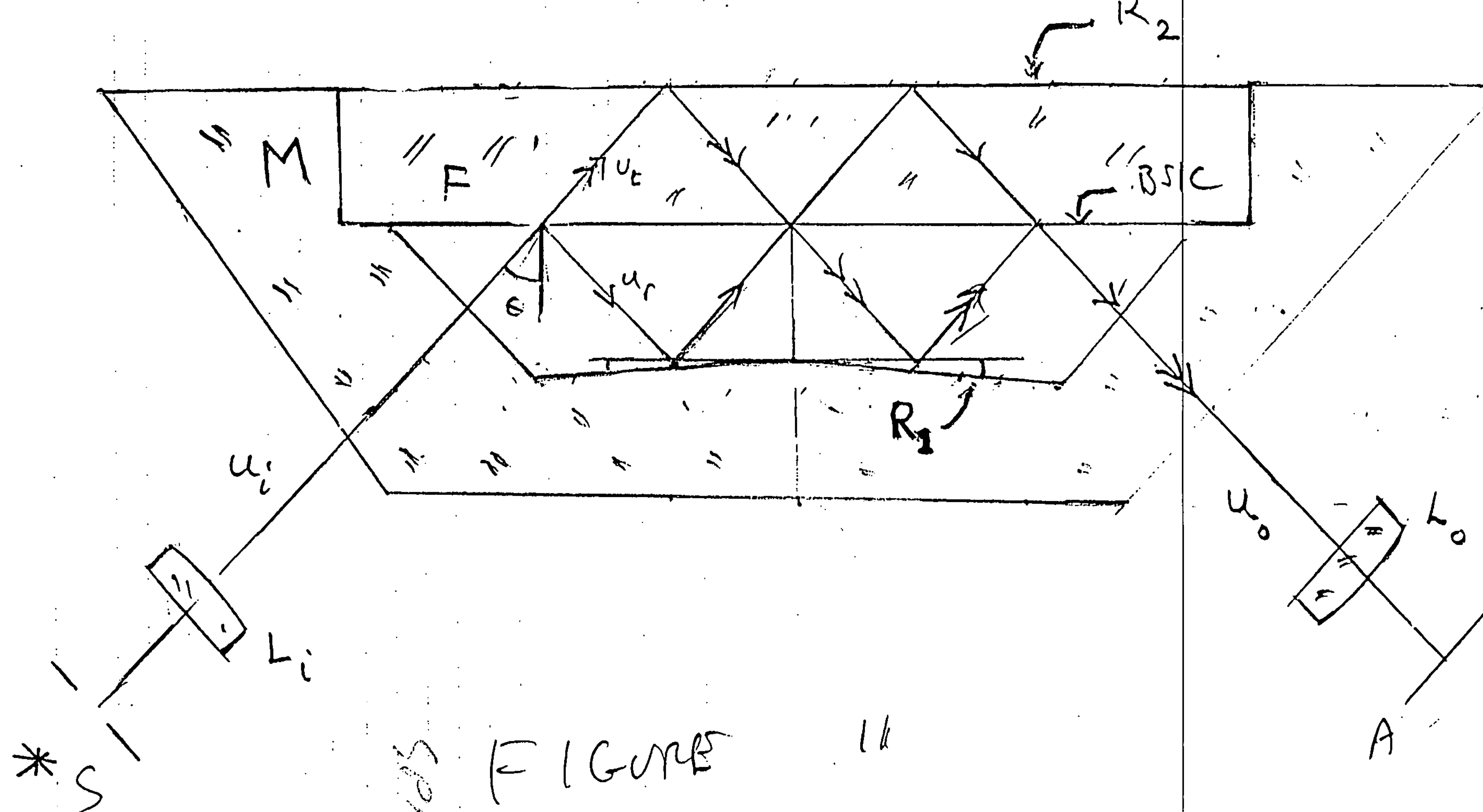

FIGURE 11

11/15

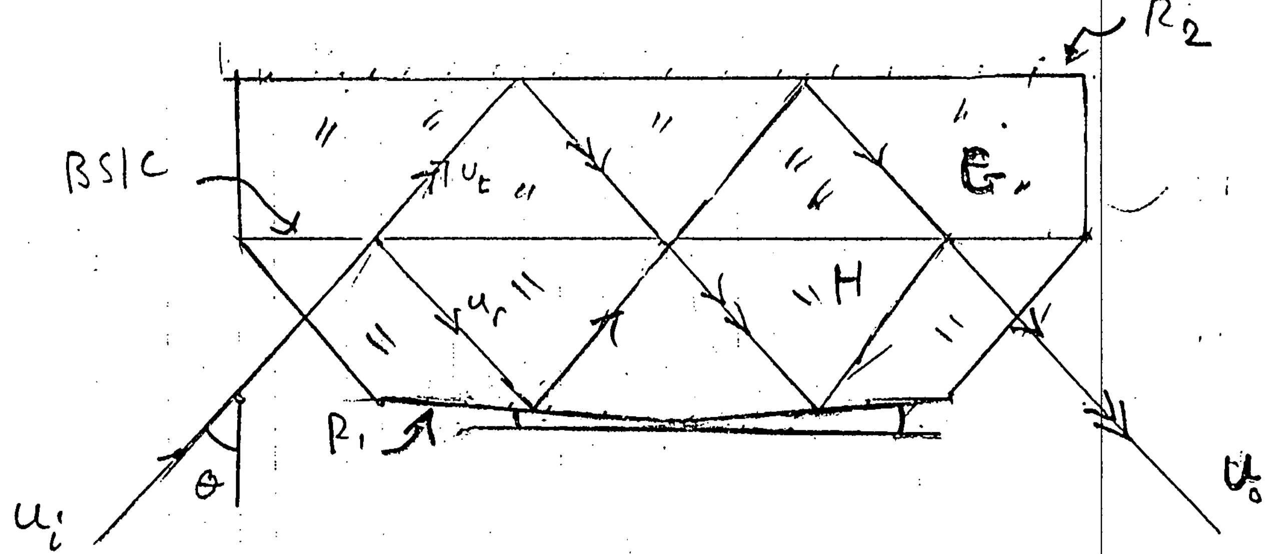

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FIGURE 12

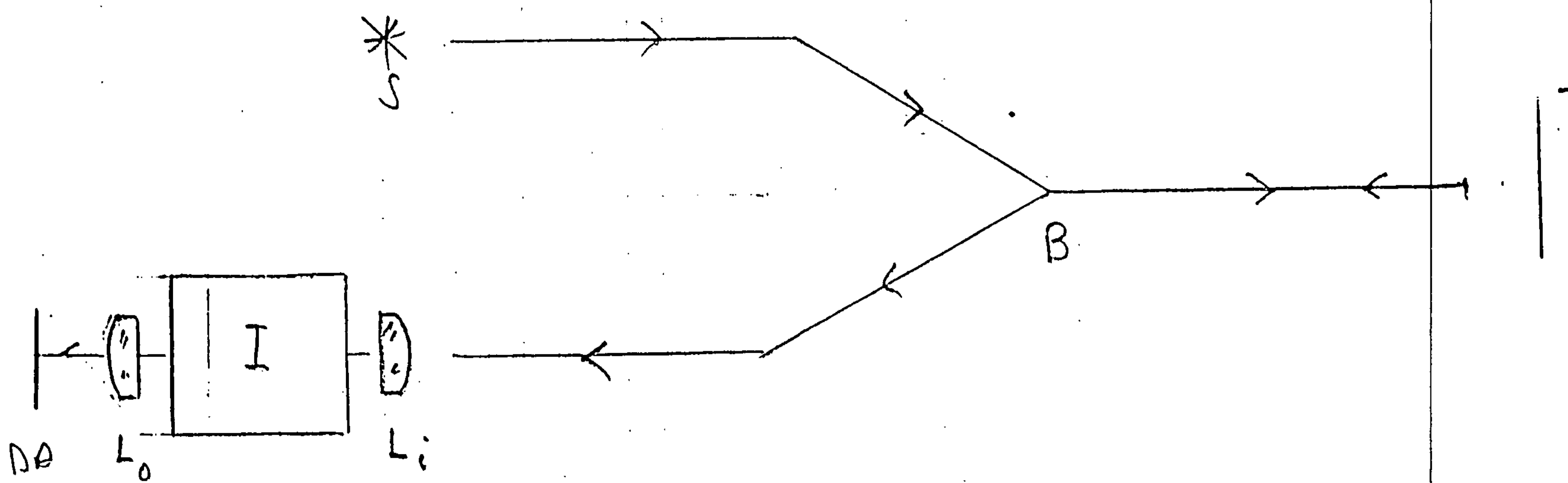
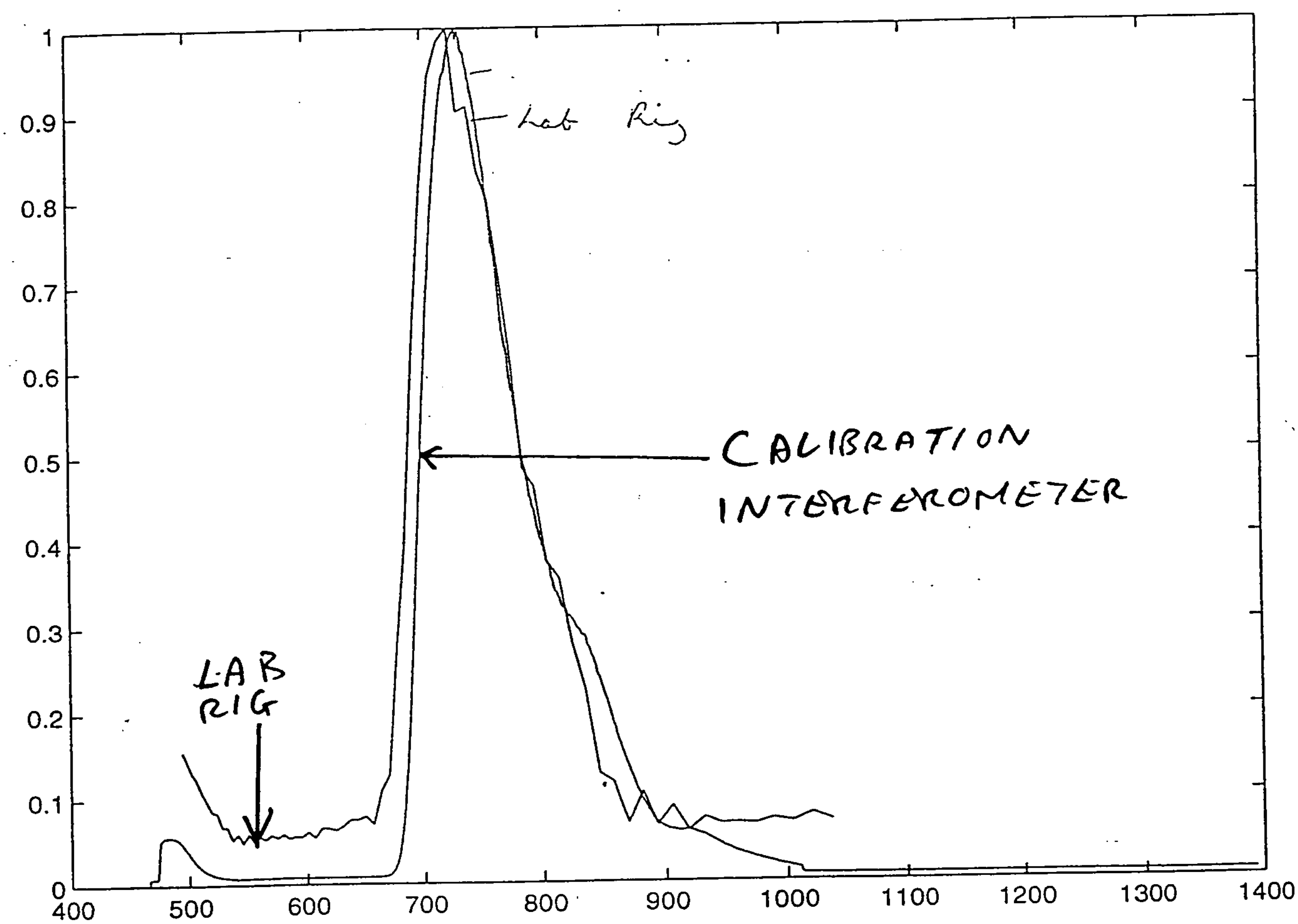


Figure 14

ROYAL BLUE (FILTER 009)



SPARE

FIGURE 15

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